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04/09/97

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Patent and Trademark Office: U.S. DEPARTMENT OF COMMERCEPTO/SB/xx (6-95)
OMB 0651-00320002/PTO
Rev. 6/95U.S. Department of Commerce
Patent and Trademark Office**NEW UTILITY PATENT
APPLICATION TRANSMITTAL**

(to be used for new applications only)

Attorney Docket Number

First Named Inventor

FRAAS

Total Pages in this Submission

Fifty five

04/09/97

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08835419**APPLICATION ELEMENTS**

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1. ☒ Fee Transmittal Form (prescribed filing fee(s))

2. Specification

☒ Abstract of the Disclosure☒ Title of the Invention☐ Cross References to Related Applications
(if applicable)☐ Statement Regarding Federally-sponsored
Research/Development (if applicable)☐ Reference to Microfiche Appendix
(if applicable)☒ Background of the Invention☒ Brief Summary of the Invention☒ Brief Description of the Drawings
(if drawings filed)☒ Detailed Description☒ Claim or Claims3. ☒ Drawing(s) (when necessary as prescribed by
35 USC 113)4. ☒ Executed Declaration5. Genetic Sequence Submission
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James C. Wray

Signature

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April 9, 1997

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Application Number		Class		Independent Claims	
Date of Receipt	Application Type	GAU		Total Claims	
	Filing Date	Foreign Filing License?		Drawing Sheets	
	Small Entity	Foreign Address?		Special Handling?	

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APPLICATION

FOR

UNITED STATES LETTERS PATENT

FOR

PRETREATMENT PROCESS TO REMOVE OXYGEN FROM COAL
EN ROUTE TO A COAL PYROLYSIS PROCESS AS A MEANS OF
IMPROVING THE QUALITY OF THE HYDROCARBON LIQUID PRODUCT

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A

Pretreatment Process to Remove Oxygen from Coal
En Route to a Coal Pyrolysis Process as a Means of
Improving the Quality of the Hydrocarbon Liquid Product

BACKGROUND OF THE INVENTION

The extraordinarily formidable difficulties presented by heavy black tar formation in processes designed to produce liquid hydrocarbons ~~from coal~~ ^{by any pyrolysis process} are indicated by the fact that these heavy tars have posed insuperable problems in over 60 y of major R&D projects all over the world, particularly in Germany, France, Great Britain, China, Japan, and the U.S.. The work in the U.S. is particularly well documented; major expenditures by the Bureau of Mines, the Office of Coal Research, D.O.E., and the big oil companies have failed to yield a commercial process. The only pilot plant sufficiently successful to continue in operation is the Encoal Plant operated by a subsidiary of the Ziegler Coal Co. in Gilbert, WY with DOE funding. It operates on Powder River Basin sub-bituminous coal. The liquid product is tar of such a high viscosity (the pour point is about 90°F) that it has been utilized only in boiler furnaces built to operate on No. 6 residual fuel oil. The main justification for operating the plant is that the char produced has been dewatered ^{and its physical structure altered to reduce the moisture it can absorb} so that its heat content per pound is much increased, and this reduces shipping costs.

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The bulk of the literature on coal pyrolysis published in the past 50 years has been concerned with either small-scale bench tests with small quantities of coal -- generally less than a gram -- or pilot plants employing gas-fluidized beds with coal through-flows of a few tons per day. The experiments in the

former were generally carried out under exquisitely controlled conditions, often with only a few particles of coal in a vacuum or an inert gas atmosphere; there is no mention of heavy black tar formation in these reports. However, in the literature on small pilot plants one finds that, whatever they might obtain in the way of a liquid product, it was generally a heavy ^{viscous} black tar. This was ordinarily attributed to polymerization of lighter hydrocarbons by a sort of catalytic action of a high concentration of activated carbon fines. These fines are inherently entrained with the hydrocarbon vapors from a gas-fluidized bed because the flow of sweep gas required to fluidize the bed of coal particles is many times the flow of vapor evolved from the coal so that a great deal of fine particles is swept up out of the fluidized bed and entrained in the sweep gas. While the larger particles can be removed in a cyclone separator, those in the micron size range are carried off with the hydrocarbon vapor to the condenser. This solid particle contamination of the hydrocarbon liquid amounts to about 10% by weight of the condensed vapor, and presents formidable filtering problems as well as liquid quality degradation caused by polymerization.

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SUMMARY OF THE INVENTION

Tests in the inventor's lab have shown that the entrainment of fine particles in the pyrolysis vapors can be reduced by a factor of about 10,000 if the gas-fluidized bed is replaced by a vibration-fluidized bed such as that in the system shown

diagrammatically in Figure 1. Thus it was expected that heavy black tar would not be a problem in the new concept of a vibrated bed coal pyrolysis system. However, when tests with small vibration-fluidized bed systems were initiated, severe difficulties with black tar formation were encountered. Efforts to cope with these problems disclosed that heavy black tar formation presents far more complex and intractable problems than had been apparent in reviews of the literature covering the R&D work with gas-fluidized beds in which researchers were overwhelmed with difficulties in trying to cope with high levels of particle entrainment, *mostly char, a specie of activated carbon.*

Other factors contributing to the formation of heavy tars *A.P.F. 4-4-97* have been mentioned in the literature. The two most important of these were thought to be small amounts of oxygen that might get into the system in one way or another and act to polymerize the unsaturated hydrocarbons in the pyrolysis vapors, while the residence time of the pyrolysis vapors in the hot zone would determine the length of time that polymerization reactions would be likely to take place. In view of the fact that the solids content of the vapors leaving the vibration-fluidized bed is so low that a cyclone separator is not needed, the residence time in the hot zone can be kept far below that inherently required in gas-fluidized bed systems, hence the latter factor was not expected to be a serious problem. Oxygen in-leakage can be kept extremely low by designing and constructing the system to be quite leak-tight, and by operating it above atmospheric pressure

so that any leakage that might occur will be gas leakage outward, not air leakage into the system.

A third factor barely mentioned in the literature was the possibility that oxygen might enter the pyrolysis process with the coal. While there are ample data in ultimate analyses on the amount of oxygen in the coal -- commonly from 2 to 7% -- nothing could be found on what fraction might be loosely bound and thus enter into polymerizing reactions, and what fraction might be tightly bound in stable molecules such as phenols and cresols that would not form active radicals that would initiate rapid polymerization reactions.

Basic Coal Chemistry

The term "coal" represents a class of carbonaceous substances formed over geological time beginning with decaying vegetation. Peat represents the first stage of the coalification process; as the process continues the moisture content decreases and the basic coal substance evolves hydrogen and oxygen as the percentage of carbon increases in the progression through the successive stages of lignite, sub-bituminous coal, bituminous coal, and anthracite which has a fixed carbon content of over 90%. The coals of primary interest for pyrolysis are the sub-bituminous and bituminous coals; these contain the largest percentage of volatile hydrocarbons that can be driven off by heating. "Pyrolysis" refers to the process of heating coal in the absence of oxygen to drive off and collect a mixture of gases and condensable vapors. The solid char residue contains

essentially all of the mineral matter (ash) in the original coal, and perhaps half of the original volatile matter. Pyrolysis is also referred to as "carbonization" and as "mild gasification" in the D.O.E. Clean Coal Technology Program. In the pyrolysis process, as the coal is heated, moisture is evolved initially, then -- as discovered by the inventors -- loosely-bound oxygen is evolved up through about 350°F. Mild pyrolysis is arbitrarily defined as the temperature range from 330 to 650°C. This temperature range gives the best yields of hydrocarbons in the motor fuel volatility range.

The invention provides a coal pretreatment apparatus. A vessel holds a bed of coal particles. A heater heats this bed to a temperature in the 200°C range, below the pyrolysis temperature of the coal. A vibrating machine produces and controls the flow of coal particles through the vessel. If a batch process is used batches of coal are moved from the pretreatment vessel to a pyrolysis retort, while preventing the entry of air that would contaminate the pretreated coal. Preferably the same apparatus is employed in such a way that it also serves to dry the coal.

A vibrating machine provides rapid mixing and heating of the coal stream entering the bed and particle motion and bed flow patterns such as to provide uniform exposure of individual particles to conditions giving a low partial pressure of oxygen with a relatively narrow spread in particle residence times.

A stream of hot furnace flue gas may be passed through a bed of hot char, coke or other material that will serve ^{to remove any} ~~as an~~ oxygen

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present
removal so that flue gas can be employed as a sweep gas stream *that*
having a low partial pressure of oxygen for heating and
pretreating the coal feed to a pyrolysis process.

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Another means of heating the coal in an atmosphere having a low partial pressure of oxygen is to employ non-condensable combustible gases in the off-gas from the pyrolysis process. This gas may be burned with less than the stoichiometric air flow rate and the resulting hot and very low oxygen content gas supplied to the pretreatment process, *provided that soot formation is avoided.*

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Ceramic balls of a larger size than the coal being processed might also be used as the heat transport medium to convey heat from a small furnace to the pretreatment bed. The larger ceramic balls can be screened from the pretreated coal and recycled through the furnace. The balls may be made of graphite, and the furnace might be fired with non-condensable ^{*combustible*} gases from the pyrolysis process. Geometric shapes other than spherical balls and/or materials other than ceramics can be employed if there are economic advantages to their use in place of roughly spherical ceramic balls.

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Placement of the pretreatment vessel close to the pyrolysis vessel minimizes heat losses and possibilities for oxygen contamination of the pretreated coal before it enters the pyrolysis bed.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic representation of a vibrating bed pyrolysis system with a pretreatment bed to remove oxygen.

Figure 2 schematically shows a coal pretreatment system incorporated in a pyrolysis process utilizing ceramic balls for transporting heat between components.

Figure 3A schematically represents the elements of molecular structures in coal, ^{including the} occurrence of ^{oxygen,} nitrogen, and sulfur.

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Figure 3B is a schematic representation of structural groups and connecting bridges in bituminous coal.

Figure 4 represents results of a preliminary study of percent CO concentration in exhaust gases in relation to the temperature in degrees fahrenheit for heat pretreatment of coal.

Figure 5 represents carbon monoxide percent concentration in exhaust gases from a pyrolysis retort during a pyrolysis process.

Figure 6 is a graphic prior art representation of gases released from coal during heating of the coal at a constant rate.

Figure 7 is a graphic representation of oxygen concentration in the off-gas during pretreatment as a function of time from the initiation of a nitrogen purge.

Figure 8 is a representation of a mass spectrograph for the liquid pyrolysis product obtained after pretreatment of coal at 450°F to remove oxygen.

Figure 9 is an expanded version of the molecular weight region from 30 to 40 for the data shown in Figure 8.

Figure 10 is a graphic representation of effects of temperature on vapor pressures of typical liquids.

Figure 11 is a graph of vapor pressure as a function of hydrocarbon concentration.

Figure 12 is a chart showing hydrocarbon emission as a function of concentration in nitrogen.

Table 1 is an identification of the molecular species shown in the mass spectrograph of Figure 8.

Table 2 is a summary of the results of the tests of the gaseous products shown in Table 1.

Table 3 presents data on the oxygen and CO concentrations in the gas^o leaving a pyrolysis retort as a function of time in a pyrolysis test conducted 12-7-96. The last column gives the total oxygen released from the coal up to that point in the test.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

There are many ways in which the invention can be employed in a power plant utilizing a fluidized bed combustor. Figure 1 shows a representative coal converter and combustor system 1 in which the vibrated bed pyrolysis system 3 is coupled to an atmospheric fluidized bed coal combustion furnace 5, commonly referred to as an AFBC. The fluidized bed 7 in this type of furnace usually consists mostly of limestone 9 or dolomite that calcines on heating to form CaO, a sorbent that gives good retention of the SO₂ formed from the sulfur in the coal as it is burned at a temperature in the 1500 to 1650°F range. Thus the

bulk of the solid particles 11 in the bed are CaO coated with a hard layer of CaSO_4 . Crushed coal 13 is fed from a supply hopper 15 through a screw feeder 17 to a vibrating bed coal deoxygenator 19 mounted next to the vibrating bed pyrolysis retort 21. The two vibrating beds are mounted on a vibrating machine 23. The

deoxygenator preheats the coal to around 400°F to drive off the

loosely bound oxygen as well as the
superficial moisture before the coal enters the pyrolysis bed, *A.P.F. & HLF 4-2-97*

which will commonly operate in the temperature range of about

1000°F to 1250°F for the *highest* ~~best~~ yield of *liquid* products (depending on the *HLF 4-2-97* coal used).

The pretreatment bed serves to remove the oxygen, moisture and the majority of the fine particles from the coal before it

reaches the pyrolysis bed. The oxygen, *water vapor* ~~moisture~~, and coal fines *A.P.F. & HLF 4-2-97*

~~are~~ flowed to the combustor 5 through pipe 25 for burning the

fines. The crushed coal particles and the hot solid particles from the combustor flow to the pyrolizer 21 as shown by line 26.

The point at which the sorbent stream 27 is tapped 28 from the combustor is chosen to minimize the amount of fines, and the high combustion air flow 29 through the fluidized bed in the furnace will naturally carry off practically all of the smaller particles as they are generated by attrition in the AFBC. Thus the amount of fine particles available for elutriation from the pyrolysis bed is minimized. Including the deoxygenator 19 in the system is also advantageous in that it preheats the coal and increases the heating rate of the particles as they enter the

pyrolysis bed. Further, the deoxygenator reduces moisture contamination of the product liquid.

To minimize the time that the product vapor is exposed to high temperature, a jet condenser 31 enclosed within a thermally-insulated sleeve 33 is mounted in the freeboard 35 above the pyrolysis bed 37 to quench the hydrocarbon vapor product with a recirculated stream of the product liquid that has been cooled to just above the boiling point of water; operating the condenser 31 in this temperature range minimizes the amount of moisture in the hydrocarbon condensate 41. The spray of droplets provides a large surface area in a compact ^{direct-contact} condenser whose effectiveness will not be degraded by the formation of tarry deposits on heat transfer surfaces. The liquid and gaseous pyrolysis products 41 leaving the jet condenser drain down to a header tank 43 having sufficient volume so that the liquid collects in the lower part of the tank while the uncondensable vapors and gases 45 leave at the top and flow to the AFBC furnace along with the water vapor 25 leaving the dryer.

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The quench liquid 39 is pumped to the jet condenser 31 by the pump 47 through the cooler 49, where it is cooled by flowing ambient water 51 in and hot water 53 out.

The stream 55 of char and sorbent leaving the pyrolysis bed is returned to the AFBC furnace by a gas lift 57 driven by a blower 59. The power required to drive the vibrating machine 23 and the gas lift blower 55 is about 0.1% of the net plant electrical output. That compares with about 0.6% for the power

required for the coal pulverizers in a conventional pulverized coal-fired steam power plant.

The flow 27 of hot sorbent from the AFBC to the vibrating beds is controlled by L-valves 61 and 63 that also serve as flow meters.

Product liquid 65 drains out through an overflow port 67 in the header tank 43 into the storage tank 69.

From the environmental standpoint, the emissions are the same as for fluidized bed combustors fired with raw coal in the conventional fashion; installation of the pyrolysis system does not require any additional equipment to control emissions.

The vibrating bed pyrolysis system is equally applicable to bubbling or entrained fluidized bed combustors, and can be used with atmospheric or pressurized fluidized bed combustors. The space required for the equipment of the vibrating bed pyrolysis system is about the same as for coal pulverizers *in a conventional pulverized coal boiler installation*.

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Figure 2 shows another representative coal pyrolysis system that employs ceramic balls as the process heating medium rather than the hot lime-ash material from a fluidized bed combustor as in the process of Fig. 1. In the process of Fig. 2 the raw crushed and screened coal flows from the coal hopper 1 to the pretreatment vessel 2 en route to the pyrolysis retort 3. A mixture of char from the coal and ceramic balls flows out of the retort 3 to a screen 4 in which the char particles, which are relatively small, fall through the screen and flow into the steam boiler furnace 5 where the char is burned to fuel the boiler.

The ceramic balls are sufficiently larger than the crushed coal so that they are skimmed off by the screen 4 and are conveyed upward via an air lift 6 to a ball heater 7. A portion of the heated balls flows out of the heater 7 to the pretreatment vessel 2 to heat the raw coal to around 400°F, while the balance of the heated balls flows to the pyrolysis retort 3 to provide the heat required for the pyrolysis process which operates at a temperature of around 1050°F. The vapors and gases driven out of the coal in the pyrolysis process flow upward to a condenser 8. The condensate drains down to a liquid storage tank 9 while the non-condensable gases flow upward to the ball heater 7 where they are burned with air in a mixture less than stoichiometric so that the oxygen concentration in the gases leaving the ball heater is less than 50 ppm. A portion of this gas flows to the pretreatment vessel 2 as a sweep gas to carry off the oxygen evolved in the pretreatment process. After picking up oxygen from the coal, that gas with its increased oxygen content is returned to the ball heater 7 where the oxygen is consumed by combustion of the pyrolysis gases.

At the risk of over-simplification, it seems worthwhile to take a brief look at the coal chemistry involved and examine some diagrams of the structure of some hydrocarbons obtained in coal pyrolysis. Coals are polymers, but since coals differ widely, no single molecular structure can represent all coals. Typical elements of the structures are shown in Figure 3A, while a synthesized model of a typical coal polymer is shown in Figure

above about 550°F non-reactive gas
3B. When heated₁ in pyrolysis in an oxygen-free₁ atmosphere, some
bonds in a structure such as that of Figure 3B are more easily
broken than others, and breaking of these bonds sets free some
lighter hydrocarbon molecules. Flash pyrolysis bench tests
indicate that, for flash pyrolysis at temperatures in the range
of 1000°F, these hydrocarbons have an average molecular weight of
about 180. Prof. A. M. Squires uses the term scissile bonds for
the more readily broken bonds, and cites "hydrogen bridges,
simple ether linkages between aromatic structures, and benzyl-
benzyl carbon bonds -- breaking in that order if the coal is
heated slowly".

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Searches of the literature have failed to find any
quantitative data on the relative importance of each of the three
factors that have been believed to affect heavy black tar
formation, i.e., the entrained carbon particle content of the
vapors leaving the retort, the residence time of the hydrocarbon
vapor in the hot zone, or the amount and form of oxygen that
might enter the system with the coal. However, after extensive
tests of small-scale pyrolysis systems in the inventor's lab, it
became evident that heavy black tar formation in the vibrating
bed coal pyrolysis system took place so rapidly in the pyrolysis
retort that it must have stemmed from rapid reactions in the gas
phase, so rapid that there is no practicable way of reducing the
residence time in the hot zone sufficiently to avoid them. Under
any of the test conditions investigated, this tar presented such
pernicious and subtle difficulties that test systems especially

designed for investigation of the problem were badly needed. Several such systems were built and tested; the results from these experiments led to a system that has consistently yielded low viscosity liquid, and this is the process presented in this patent.

There is nothing in the literature to indicate the precise sequence of the chain reactions involved in ^{these rapid gas phase} ~~the~~ polymerization reactions triggered by free oxygen in the pyrolysis retort.

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These reactions are so complex that it is exceedingly difficult to make experimental determinations of the steps in the reactions. An excellent recent paper by Carpenter, cited as a reference, indicates that the dynamics of these reactions is so complex that an analytical solution seems out of the question.

Inventors' Experiments

O₂ and CO Release from the Coal

While there are many mentions in the literature of oxygen as a probable cause of heavy tar formation, the quantitative data on possibly acceptable oxygen concentrations found in the literature weren't very helpful. Most of the quantitative data on oxygen in coal were in ultimate analyses that cited values commonly running from 2% to 7% O₂ by weight of the coal, but these references gave no indication of what fraction of that oxygen might come off as free oxygen when the coal was heated and what fractions might come off as H₂O, CO, CO₂, phenols, cresols, or other more complex compounds.

The inventors' tests began with an investigation to determine the release of CO as a function of heating time in a nitrogen atmosphere because a CO meter was readily available. These tests yielded curves for the CO concentration in the exhaust gas as a function of time such as those in Figs. 4 and 5 for the pretreatment and pyrolysis processes respectively. These curves show high CO release rates in sporadic bursts that occurred during slow heating at particular temperatures of about 121, 177, 232, 288, and 510°C (250, 350, 450, 550 and 950°F). The high releases found at low temperatures are remarkably different from the complete absence of CO releases up to a temperature of 450°C, or 850°F, shown in Figure 6, which is typical of those in the literature. Note that these system tests indicate that the CO release comes in bursts at particular temperature regions, at least for the coals tested.

When an oxygen meter became available, the same test procedure employed for the CO release rate was followed. The degassing pretreatment was started at room temperature and the oxygen concentration and coal temperature were observed as a function of time. The results are shown in Figure 7. While the amount of oxygen evolved is much less than the amount of CO, it is still substantial; oxygen is released even at room temperature when the coal is treated with a sweep gas having an oxygen concentration below 50 ppm so that the oxygen partial pressure is of the order of 50 μ m of Hg. When the coal is heated, as in the cases for which the CO release rate was measured, bursts of

oxygen release occur at about 121, 177, and 204°C (250, 350, and 400°F). *No further releases of oxygen at temperatures above 400°F have been observed.* The effectiveness of this pretreatment of the coal in removing oxygen to yield a low viscosity liquid hydrocarbon

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product from a pyrolysis system has now been demonstrated in ten different tests with a small pyrolysis system. When a test tube containing the product liquid is shaken, the liquid is not a heavy black tar but appears to have the viscosity of No. 2 fuel oil, i.e., not much greater than water. Six other tests with the same pyrolysis system but without the pretreatment have all yielded only a heavy black tar with a viscosity so high that it has taken many seconds for a few cubic centimeters to flow from one end of a test tube to the other with an inclination of about 20 deg.

Polymerization Mechanisms

A key element in the inventors' development of this new pretreatment concept is the discovery that there appear to be two distinctly different contaminants that are responsible for the production of the heavy black tars that have plagued all previous coal pyrolysis systems. The first contaminant is in the form of fine particles of char (a specie of activated carbon) that act as catalysts to polymerize unsaturated liquid hydrocarbons at a relatively slow rate over a period of days or weeks at room temperature. The second contaminant is free oxygen which at pyrolysis process temperatures forms active ions that trigger rapid polymerization reactions that take place in times of the order of a second. Thus the first step in avoiding heavy tar

formation is the use of a vibration-fluidized bed to reduce the solid particle content of the pyrolysis vapor by a factor of at least 10,000 over that for gas-fluidized beds. This is a necessary but not sufficient condition; it is also essential that the oxygen concentration in the pyrolysis retort be kept to extremely low levels. To accomplish this the oxygen content of the sweep gas must be kept below about 50 ppm, and the adsorbed or loosely bound oxygen in the coal fed to the process must be largely removed by a pretreatment process as described in this patent application.

Significant Observations

One of the most significant observations made in the course of the inventors' experiments was that in a glass retort test a yellow fog of aerosol droplets began to form a few millimeters above the free surface of the coal and was carried off to the condenser with the sweep gas. A dark orange varnish deposit appeared on the glass walls of the retort and the passages to the condenser, and a viscous dark liquid deposit built up on the ice-water-cooled wall of the condenser. When an oxygen meter was procured it was found that laxity in refilling a nitrogen cylinder at the gas supplier had given an oxygen content of 53 ppm in the nitrogen instead of the 3 ppm maximum nominally specified. This test showed the rapidity with which a small amount of oxygen in the nitrogen sweep gas induced polymerization of light hydrocarbon vapors into tars whose boiling point was so high that they immediately condensed into micron-size droplets

before the vapor had moved into a lower temperature region. The superficial velocity of the vapors leaving the surface of the bed of coal particles was about 3 mm/s indicating that the aerosol particles were produced in roughly a second. In this and other experiments microscopic examinations disclosed that the aerosol droplets of tar were sufficiently sticky that they tended to agglomerate into clusters and deposit out on walls or in filters, commonly as clusters of microspheres. Similar deposits of tar microspheres were found in all of the tests in which a yellow "smoke" was observed where glass elements permitted direct observations.

The use of freshly-crushed coal coupled with a drying heat treatment had avoided heavy tar formation in some ORNL coal pyrolysis tests carried out by R. Graves in 1983. In these tests the coal was heated slowly in static batches so that there was no evolution of fines with the vapor. The batches were well sealed and swept with high purity argon. The inventors carried out a seemingly similar drying operation for a vibrating system test, but got heavy black tar. However, the ORNL drying was carried out in an argon atmosphere with a strong sweep gas flow of pure argon, whereas the coal drying for the inventors' test was done in air, which permitted continuous oxidation and/or CO formation even while some oxygen or CO might have been driven off.

Experiments by previous investigators have included many other measures that might serve to improve the quality of the product liquid by reducing the amount of unsaturated

hydrocarbons. These measures include using sweep gases other than nitrogen, e.g., hydrogen, steam, CO₂, He, A, methane, or a good hydrogen donor such as tetralin (see Figure 2), and will be investigated in future tests. Different types of coal are likely to behave differently, and the temperatures used at different stages in the process may prove important. Yet another factor may be the heating rate.

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Composition of Liquid and Gaseous Products

Arrangements were made for analyses of samples of the liquid and gaseous products from a pyrolysis test run with pretreated coal. The analyses were carried out by personnel at NREL who have been working on the pyrolysis of wood wastes. A mass spectrograph test of the liquid yielded Figs. 8 and 9 from which they prepared Table 1. Table 2 summarizes the results of the NREL tests of the gaseous product. A particularly significant result is that the mass spectrographic analysis of the liquid product showed no sign of sulfur, sodium, or potassium, hence this liquid should be usable as a gas turbine fuel with no need for refining other than possibly a simple filtration operation. However, the product liquid should be fed to burners within 3 weeks of its production because after 3 weeks it begins to polymerize and become viscous.

Hydrocarbon Losses in the Pretreatment Process

Three charts have been prepared to make quick estimates of the possibility of serious losses of the lighter hydrocarbons in the sweep gas if one looks simply at their vapor pressures.

Actual losses should be much lower because these hydrocarbon groups are chemically bound in the coal polymer, but the bonds for some are sufficiently weak so that they may be broken at temperatures below 316°C (600°F). If they are released from the polymer, and if the nitrogen sweep gas flow is made sufficiently high to carry off water vapor and oxygen expeditiously, these charts show that hydrocarbons in the motor fuel volatility range have vapor pressures sufficiently high that appreciable quantities may be carried off in the sweep gas. Thus a key question is the rate at which lighter hydrocarbons may be released from the polymer as a function of temperature.

The first chart, Figure 10, is for the vapor pressures of some typical liquids as a function of temperature. This was prepared to investigate the question for short periods of coal exposure at pretreatment temperatures. It shows that the vapor pressures of motor fuel hydrocarbons can easily run in the range 10 to 100 mm in the 100 to 500°F temperature range. Instrumentation is available to obtain rapid responses to hydrocarbon concentrations in nitrogen in the range of 10 to 30,000 ppm. While these instruments normally read in percent or in ppm by volume, the construction of charts is simplified if the values are in terms of ppm by weight rather than by volume.

Figure 11 was constructed from Figure 10 to show the hydrocarbon concentration in nitrogen expressed in ppm by weight as a function of the vapor pressure for some typical species differing widely in molecular weight. Figure 12 was derived from

Figure 11 to give the hydrocarbon emissions in terms of grams per minute per gram of coal as a function of the hydrocarbon concentration in ppm by weight. Values are plotted for a series of sweep gas flow rates expressed as cubic centimeters per second per gram of coal in the retort. The formula used in preparing each chart is shown at the top of the chart.

These charts show that one can easily lose the bulk of the lighter hydrocarbons obtainable from coal if they are released from the polymer. Thus the key question becomes the rate at which they are released from the coal polymer as a function of temperature. One suspects that each specie may be released in little bursts as is the case with CO.

Amount of Oxygen to Produce a Substantial Amount of Tar

A key question is the amount of oxygen contamination that might produce a significant amount of heavy black tar. If one assumes a molecular weight for the tar of 3200, and that one atom of oxygen might induce the polymerization of a molecule of tar, the weight of oxygen would run 0.5% of the tar. Turning to sources of oxygen, Table 3 gives data for the removal of oxygen from a coal sample by degassing at temperatures up to 600°F; the oxygen removed ran 0.178% of the product liquid. Other tests gave similar values. If the nitrogen sweep gas is contaminated with 50 ppm of oxygen as in the case of Table 3, the amount of oxygen would run almost ten times greater, or about 1% of the product liquid. These very crude estimates indicate that the amounts of oxygen in the nitrogen sweep gas during the pyrolysis

process and the amount of oxygen removed from the coal in the pretreatment process may be sufficient to explain the tar formation. Further, note that observations in some glass system tests showed that films of tar on the condenser-test-tube wall were too viscous to flow, but, when the test tube was shaken, the low viscosity liquid in the bottom of the test tube quickly washed the viscous tar off the walls. Thus the viscosity of the hydrocarbon liquid product of pyrolysis is doubly sensitive to the formation of a small amount of tar because any tar that is formed reduces the amount of solvent available to reduce the tar viscosity. Anyone who has poured a little gasoline into roofing tar knows that it doesn't take much gasoline to thin the tar from a stiff paste to a liquid that handles well with a paint brush.

The pretreatment process for removing the oxygen that would otherwise be evolved from the coal as molecular oxygen during the coal pyrolysis process entails sweeping the coal particles with a gas containing less than 100 ppm of oxygen while heating the coal to around 200°C (392°F). While this might be done in many different ways, a typical system employing a complex-mode vibration-fluidized bed is shown in Figure 1. The vibratory mode should be chosen to provide good continuous mixing of all of the coal particles in the bed with the sweep gas, and a narrow spread in the transit times of the particles circulated through the bed so that they are processed to give a uniformly low content of oxygen that will be released as molecular oxygen during the pyrolysis process. This also implies that the vibration mode

should be such that the particles will be heated rapidly to the pretreatment process temperature, and that the bed temperature should be uniform. Further, the bed temperature should be controlled to be sufficiently high and the residence time sufficiently long to remove most of the molecular oxygen and thus reduce the oxygen release during pyrolysis to an acceptable level. At the same time, the pretreatment temperature should not be so high or maintained so long as to result in serious losses of hydrocarbon vapors. Appropriate values for these parameters will depend on the particular coal being processed as well as the market price dependence on the quality of the product liquid. Other factors influencing these choices include the character and features of the particular pyrolysis process and the effectiveness of additives to the liquid product. For example, additives such as hydrogen donors like tetralin may be desirable as a means of extending the storage life of the liquid.

The bed for the pretreatment process might be heated in any of many different ways including gas-firing, electric resistance, or microwave heaters. The system chosen for heating the bed of Figure 1 is a by-pass stream of hot sorbent particles circulated from a fluidized bed combustion furnace so that the sorbent flows directly into the stream of coal particles to be heated. In this instance the pretreatment bed will serve as both a dryer for the coal and a means for removing oxygen. This arrangement will provide a low-cost source of heat with no need for heat transfer surfaces, and will heat the particles to the design bed

temperature in only a few seconds. It has been demonstrated in cold flow tests that complex-mode vibration-fluidized beds can be operated to give particle motions and flow patterns that provide the desired characteristics of rapid mixing rates with relatively narrow spreads in particle transit times.

The various systems that might be employed for coal pyrolysis processes differ so widely that the particular design of vessel for the pretreatment process could take many different forms, and the same is true of the means chosen for accomplishing the heating. However, the purpose of the operation would be the same, namely; removing adsorbed and ^{loosely-}~~highly~~ bonded oxygen from the coal by heating the coal to a temperature in the 200°C range while maintaining a low partial pressure of oxygen in the particle bed by evacuation or with a sweep gas having a low oxygen content.

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While the invention has been described with reference to specific embodiments, modifications and variations of the invention may be constructed without departing from the scope of the invention, which is defined in the following claims.

I claim:

1. A coal pyrolysis pretreatment apparatus comprising a pretreatment vessel for holding a bed of coal particles, a preheater for heating the bed of coal particles to a temperature below the coal pyrolysis temperature range, an enclosure around the vessel for preventing air from contacting the bed of coal particles, and ^{@ very low oxygen sweep gas or a vacuum} ~~oxygen remover~~ for removing the oxygen released from the heated coal particles and transporting it away from the enclosure so that the partial pressure of oxygen in the pretreatment region is kept low.

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2. The apparatus of claim 1, further comprising an inlet for feeding coal particles to the vessel and an outlet for removing particles from the vessel.

3. The apparatus of claim 1, further comprising a pyrolysis retort near the vessel and transfer passages for transferring heated coal particles from the pretreatment vessel to the pyrolysis retort while preventing entry of air.

4. The apparatus of claim 1, wherein the pretreatment vessel further serves as a dryer for removing moisture from the coal.

5. The apparatus of claim 1, further comprising a vibrating machine connected to the vessel for vibrating the vessel and providing rapid mixing and heating of coal particles entering the bed from the input to provide uniform removal of oxygen from coal particles.

6. The apparatus of claim 1, further comprising a gas inlet connected to the vessel for contacting the coal particles in the bed with a sweep gas of low oxygen content, and a gas outlet connected to the enclosure for removing the sweep gas before the oxygen extracted from the coal particles builds up in the sweep gas and inhibits the deoxidation process.

7. The apparatus of claim 6, further comprising a flue gas source connected to the gas input for supplying low oxygen concentration flue gas as an oxygen removal sweep gas to the bed of coal.

8. The apparatus of claim 1, further comprising a collector for collecting non-condensable combustible gases from coal pyrolysis, and a burner for partially burning the collected non-condensable combustible gases and supplying hot, partially combusted non-condensable gases from the burner to the bed of coal particles to serve as a sweep gas for heating and removing oxygen from the bed of coal particles.

9. The apparatus of claim 6, further comprising a source of carbon monoxide connected to the gas input for supplying carbon monoxide to the bed of coal particles and removing oxygen from the coal particles with the carbon monoxide.

10. The apparatus of claim 1, wherein the heater comprises a furnace holding ceramic balls of a size larger than coal particles in the bed, and provisions for circulating the ceramic balls from the furnace to the bed of coal particles for heating

the coal particles in the pretreatment vessel and recycling the balls through the furnace for reheating.

11. A coal pyrolysis pretreatment process comprising heating the bed of coal particles to a temperature below the coal pyrolysis temperature range, preventing air from contacting the bed of coal particles, and removing oxygen released from the heated coal particles from the enclosure before subjecting the coal to pyrolysis.

12. The process of claim 11, further comprising inputting coal particles to a pretreatment vessel and removing particles from the vessel.

13. The process of claim 11, further comprising transferring heated coal particles from the vessel to a pyrolysis retort near the vessel while preventing entry of air.

14. The apparatus of claim 11, further comprising removing moisture from the coal.

15. The process of claim 13, further comprising vibrating the vessel and providing rapid mixing and heating of coal particles entering the bed from the input to provide uniform removal of oxygen from coal particles.

16. The apparatus of claim 11, further comprising contacting the coal particles in the bed with an oxygen removal gas, and removing the oxygen removal gas with the oxygen removed from the coal particles.

17. The process of claim 16, further comprising supplying low oxygen flue gas as the oxygen removal gas to the bed of coal.

18. The process of claim 11, further comprising collecting non-condensable combustible gases from coal pyrolysis, and burning the collected non-condensable combustible gases for heating the bed of coal, and supplying partially combusted collected non-condensable gases from the burner to the bed of coal particles for removing oxygen from the bed of coal particles.

19. The process of claim 16, further comprising supplying carbon monoxide to the bed of coal particles and removing oxygen from the coal particles with the carbon monoxide.

20. The process of claim 11, wherein the heating comprises heating in a furnace ceramic balls of a size larger than coal particles in the bed, and circulating the heated ceramic balls from the furnace to the bed of coal particles for heating the coal particles in the vessel and recycling the balls through the furnace.

21. The process of claim 20, further comprising circulating some of the ceramic balls to the vessel for pretreating the coal by preheating the coal and removing oxygen, flowing coal from the pretreatment vessel to a pyrolysis retort and circulating some of the ceramic balls to the pyrolysis retort for pyrolysis of the coal.

22. The process of coal pyrolysis pretreatment using the apparatus of claim 1.

23. The process of coal pyrolysis pretreatment comprising contacting coal particles in a bed with an oxygen removal gas,

removing the oxygen removal gas with oxygen removed from the coal particles, and transferring the pretreated coal to a pyrolysis retort in the absence of air.

ABSTRACT OF THE DISCLOSURE

Pretreatment removes oxygen from coal being fed to coal pyrolysis processes. The pretreatment improves the quality of the liquid produced. Free molecular oxygen present in the hot zone of the pyrolysis process causes the low molecular weight hydrocarbons that are evolved to polymerize rapidly into heavy, viscous, black tars that drastically reduce the value of the liquid product. A major source of free oxygen in a coal pyrolysis process is from the coal itself. Some oxygen in ~~run~~ ^{commercial} ~~of the mine~~ coal is present as adsorbed or loosely-bound molecular oxygen that can be removed by heating the coal to about 350°F (177°C) either under vacuum, or in a sweep gas in which the oxygen partial pressure is kept less than around 100 μ m. It is the loosely-bound oxygen, not the tightly-bound oxygen present in the form of compounds such as cresols and phenols, that triggers chain reactions that convert the lower molecular weight (100 to 200) hydrocarbons into the high molecular weight (2000 to 5000) tars that are so viscous that their commercial value is about that of the lowest grade fuel oil. Tests carried out with small pyrolysis systems in a laboratory have demonstrated that the process can be carried out by heating the coal in a vacuum, but this introduces troublesome problems such as vacuum-air locks, air in-leakage, and strength requirements in vessel walls. These problems of vacuum systems can be avoided by using a sweep gas with a low content of oxygen such as nitrogen or cleaned and deoxygenated furnace stack gas. A batch of crushed coal can be

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treated in a static bed, or a steady-flow system with the bed fluidized by gas flow or by vibration can be employed to minimize the residence time required for the oxygen removal process. The coal residence time and process temperatures selected will depend on the type of coal and the system integration requirements. The hot treated coal can be fed directly to the pyrolysis process.

Peak#	Ret Time	Type	Width	Area	Start Time	End Time
1	3.222	BB	0.048	30393316	3.171	3.361
2	14.154	BB	0.076	313283607	13.912	14.317 - Phenol
3	16.767	BV	0.062	226782918	16.512	16.852 5 -cresol
4	17.528	BV	0.099	645315429	17.192	17.740 -p-cresol
5	18.514	VB	0.069	48860748	18.440	18.701
6	19.588	BV	0.082	59120967	19.406	19.753 -dimethylphenol
7	19.936	PV	0.098	322802782	19.753	20.065 -2,4 dimethylphenol
8	20.590	BB	0.104	331638422	20.341	20.739 2,6 dimethylphenol
9	20.873	BB	0.060	36879860	20.772	20.948 C ₂ phenol
10	21.099	BV	0.059	33990136	21.040	21.184 naphthalene
11	21.356	PV	0.077	90845735	21.184	21.417 C ₂ phenol
12	21.527	VV	0.151	136310629	21.417	21.668 dihydroxy benzene
13	22.439	BV	0.076	64112416	22.333	22.510 C ₃ phenol
14	22.758	PV	0.062	68611382	22.634	22.829 C ₃ phenol
15	23.412	BV	0.138	240115887	23.019	23.553 ?
16	23.646	VV	0.079	47741586	23.553	23.712
17	24.320	VV	0.170	207909906	24.069	24.458 methyl catecol
18	24.538	VV	0.076	79325325	24.458	24.605 methyl naphthalene
19	24.653	VV	0.055	38565908	24.605	24.742 n-C ₁₃
20	25.046	PV	0.125	118270515	24.742	25.117 methyl naphthalene
21	25.793	PV	0.094	59603420	25.659	25.871 ?
22	26.991	BV	0.147	111756150	26.665	27.083 C ₂ catecol
23	27.478	VV	0.071	74153041	27.310	27.554 n-C ₁₄
24	28.217	VV	0.155	111996448	28.057	28.318 ?
25	29.150	PB	0.126	79288182	28.893	29.272 hydrocarbon
26	30.134	VV	0.066	71278688	29.984	30.291 n-C ₁₅ 212
27	30.411	PV	0.092	38697487	30.291	30.500 -C ₃ naphthalene
28	32.644	VV	0.067	70995925	32.585	32.800 n-C ₁₆ 226
29	33.055	VV	0.131	89973356	32.800	33.126 methyl naphthal
30	33.815	PV	0.146	99261970	33.420	33.917 ?
31	35.017	BV	0.076	72696374	34.649	35.080 hydrocarbon 230
32	35.165	VV	0.068	58509299	35.080	35.250 hydrocarbon-ole 238
33	35.991	PB	0.126	66195337	35.818	36.125
34	37.268	VV	0.077	49827041	37.184	37.419 hydrocarbon ole
35	38.913	PV	0.096	44028359	38.654	38.954 hydrocarbon mix
36	39.013	VV	0.083	65757311	38.954	39.111
37	39.243	VV	0.108	41825527	39.111	39.323 hydrocarbon-mix
38	39.407	VV	0.078	31700091	39.323	39.464
39	39.576	VV	0.206	82404413	39.464	39.804
40	40.336	VV	0.076	99687158	40.176	40.503 hydrocarbon
41	40.790	PV	0.125	67313401	40.614	40.882
42	40.949	VV	0.094	50579033	40.882	41.001
43	41.074	VV	0.100	52058420	41.001	41.130
44	41.411	VV	0.075	94054622	41.305	41.535
45	42.054	PV	0.189	136427968	41.639	42.185-hc
46	42.324	VB	0.085	94923542	42.185	42.528
47	43.116	VV	0.090	163284484	42.861	43.181-hc
48	43.301	VV	0.114	64892843	43.181	43.410
49	43.630	PV	0.115	37686533	43.410	43.684
50	43.830	VV	0.078	137793990	43.684	43.939-hc
51	43.996	VV	0.084	32775013	43.939	44.036
52	44.107	VV	0.097	48161669	44.036	44.164
53	44.260	VV	0.084	54499174	44.164	44.318
54	44.481	VV	0.065	114007997	44.318	44.560-hc
55	44.871	VV	0.095	46641140	44.795	44.966
56	45.083	VV	0.050	74068060	44.966	45.161

Table 1 Identification of the molecular species shown in the mass spectrograph of Fig. 8. (Courtesy of NREL.)

Table 2 NREL Analysis of Gas Sample from Flask No. 3
of Glass System Pyrolysis Test No. 5 of 9-6-96

Analysis Made with MTI Gas Chromatograph
by Bob Evans 303 384 5284

Gas	Percent	ppm	Vapor Press. mm Hg @ °C	
N ₂	90	900,000		
CH ₄	3.5	35,000		
H ₂	1.8	18,000		
CO	0.4	4,000		
CO ₂	1.7	17,000		
Ethane	0.7	7,000	600	-94
Ethylene	0.2	2,000		
Propane	0.2	2,000	600	-48
Propylene	0.16	1,600		
n Butane	0.09	900	900	3.8
1 Butene	0.03	300		
iso Butene	0.02	200		
cis2 Butene	0.03	300		
trans 2 Butene	0.06	600		
n Pentane	0.05	500	200	2
iso Pentane	0.01	100	200	-5

Note that the above table indicates that any hydrocarbons with vapor pressures less than 200 mm Hg @ 0°C would have condensed out of the pyrolysis gas at the ice-water bath temperature, hence would have been present in the off-gas collection flask in concentrations below about 100 ppm. Thus compounds as volatile as pentane were probably present in the liquid product. The analysis of the liquid should show this.

Hg

**VERIFIED STATEMENT CLAIMING SMALL ENTITY STATUS
(37 CFR 1.9(f) & 1.27(b))--INDEPENDENT INVENTOR**

Docket Number (Optional)

Applicant or Patentee: Arthur P. Fraas, Richard L. Furgerson and Harold L. Falkenberry

Serial or Patent No.: _____

Filed or Issued: _____

Title: Pretreatment Process to Remove Oxygen from Coal En Route to a Coal Pyrolysis Process as a Means of Improving the Quality of the Hydrocarbon Liquid Product

As a below named inventor, I hereby declare that I qualify as an independent inventor as defined in 37 CFR 1.9(c) for purposes of paying reduced fees to the Patent and Trademark Office described in:

- ☒ the specification filed herewith with title as listed above.
☐ the application identified above.
☐ the patent identified above.

I have not assigned, granted, conveyed or licensed and am under no obligation under contract or law to assign, grant, convey or license, any rights in the invention to any person who would not qualify as an independent inventor under 37 CFR 1.9(c) if that person had made the invention, or to any concern which would not qualify as a small business concern under 37 CFR 1.9(d) or a nonprofit organization under 37 CFR 1.9(e).

Each person, concern or organization to which I have assigned, granted, conveyed, or licensed or am under an obligation under contract or law to assign, grant, convey, or license any rights in the invention is listed below:

- ☒ No such person, concern, or organization exists.
☐ Each such person, concern or organization is listed below.

Separate verified statements are required from each named person, concern or organization having rights to the invention averring to their status as small entities. (37 CFR 1.27)

I acknowledge the duty to file, in this application or patent, notification of any change in status resulting in loss of entitlement to small entity status prior to paying, or at the time of paying, the earliest of the issue fee or any maintenance fee due after the date on which status as a small entity is no longer appropriate. (37 CFR 1.28(b))

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application, any patent issuing thereon, or any patent to which this verified statement is directed.

Arthur P. Fraas

NAME OF INVENTOR

Arthur P. Fraas
Signature of inventor

Date

April 4, 1997

NAME OF INVENTOR

Signature of inventor

Date

NAME OF INVENTOR

Signature of inventor

Date

Type a plus sign (+) inside this box →

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Patent and Trademark Office

Attorney Docket Number

First Named Inventor

FRAAS

DECLARATION

☒ Declaration Submitted with Initial Filing OR ☐ Declaration Submitted after Initial Filing

COMPLETE IF KNOWN

Application Number

Filing Date

Group Art Unit

Examiner Name

As a below named inventor, I hereby declare that:

My residence, post office address, and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

Pretreatment Process to Remove Oxygen from Coal En Route to a Coal Pyrolysis Process as a Means of Improving the Quality of the Hydrocarbon Liquid Product

(Title of the invention)

the specification of which

☒ is attached hereto

OR

☐ was filed on (MM/DD/YYYY)

as United States Application Number or PCT International

Application Number

and was amended on (MM/DD/YYYY)

(if applicable).

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment specifically referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in Title 37 Code of Federal Regulations, § 1.58.

I hereby claim foreign priority benefits under Title 35, United States Code § 119 (a)-(d) or § 365(b) of any foreign application(s) for patent or inventor's certificate, or § 365 (a) of any PCT international application which designated at least one country other than the United States of America, listed below and have also identified below, by checking the box, any foreign application for patent or inventor's certificate, or of any PCT international application having a filing date before that of the application on which priority is claimed.

Prior Foreign Application Number(s)	Country	Foreign Filing Date (MM/DD/YYYY)	Priority Not Claimed	Copy Attached?	
				YES	NO
			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

☐ Additional foreign application numbers are listed on a supplemental priority sheet attached hereto:

I hereby claim the benefit under Title 35, United States Code § 119(e) of any United States provisional application(s) listed below.

Application Number(s)	Filing Date (MM/DD/YYYY)	<input type="checkbox"/> Additional provisional application numbers are listed on a supplemental priority sheet attached hereto.

Burden Hour Statement: This form is estimated to take .4 hours to complete. Time will vary depending upon the needs of the individual case. Any comments on the amount of time you are required to complete this form should be sent to the Chief Information Officer, Patent and Trademark Office, Washington, DC 20231, and to the Office of Information and Regulatory Affairs, Office of Management and Budget (Project 0651-0032), Washington DC 20503. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Assistant Commissioner for Patents, Washington, DC 20231.

DECLARATION

Page 2

I hereby claim the benefit under Title 35, United States Code § 120 of any United States application(s), or § 365(c) of any PCT international application designating the United States of America, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application in the manner provided by the first paragraph of Title 35, United States Code § 112, I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations § 1.56 which became available between the filing date of the prior application and the national or PCT international filing date of this application.

U.S. Parent Application Number	PCT Parent Number	Parent Filing Date (MM/DD/YYYY)	Parent Patent Number (if applicable)

☐ Additional U.S. or PCT international application numbers are listed on a supplemental priority sheet attached hereto.

As a named inventor, I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith:

Firm Name James C. Wray

Payor Number (if applicable)

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Name of Sole or First Inventor: ☐ A petition has been filed for this unsigned inventor

Given Name	Arthur	Middle Initial	P.	Family Name	Fraas	Suffix	
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Inventor's Signature *Arthur P. Fraas* Date April 4, 1997

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+

ADDITIONAL INVENTOR(S)
Supplemental Sheet

Name of Additional Joint Inventor, if any:				<input type="checkbox"/> A petition has been filed for this unsigned inventor			
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Inventor's Signature						Date	
RESIDENCE: City		State		Country		Citizenship	
POST OFFICE ADDRESS							
City		State		Zip		Country	
Name of Additional Joint Inventor, if any:				<input type="checkbox"/> A petition has been filed for this unsigned inventor			
Given Name		Middle Initial		Family Name		Suffix	
Inventor's Signature						Date	
RESIDENCE: City		State		Country		Citizenship	
POST OFFICE ADDRESS							
City		State		Zip		Country	
Name of Additional Joint Inventor, if any:				<input type="checkbox"/> A petition has been filed for this unsigned inventor			
Given Name		Middle Initial		Family Name		Suffix	
Inventor's Signature						Date	
RESIDENCE: City		State		Country		Citizenship	
POST OFFICE ADDRESS							
City		State		Zip		Country	

☐ Additional inventors are being named on supplemental sheet(s) attached hereto

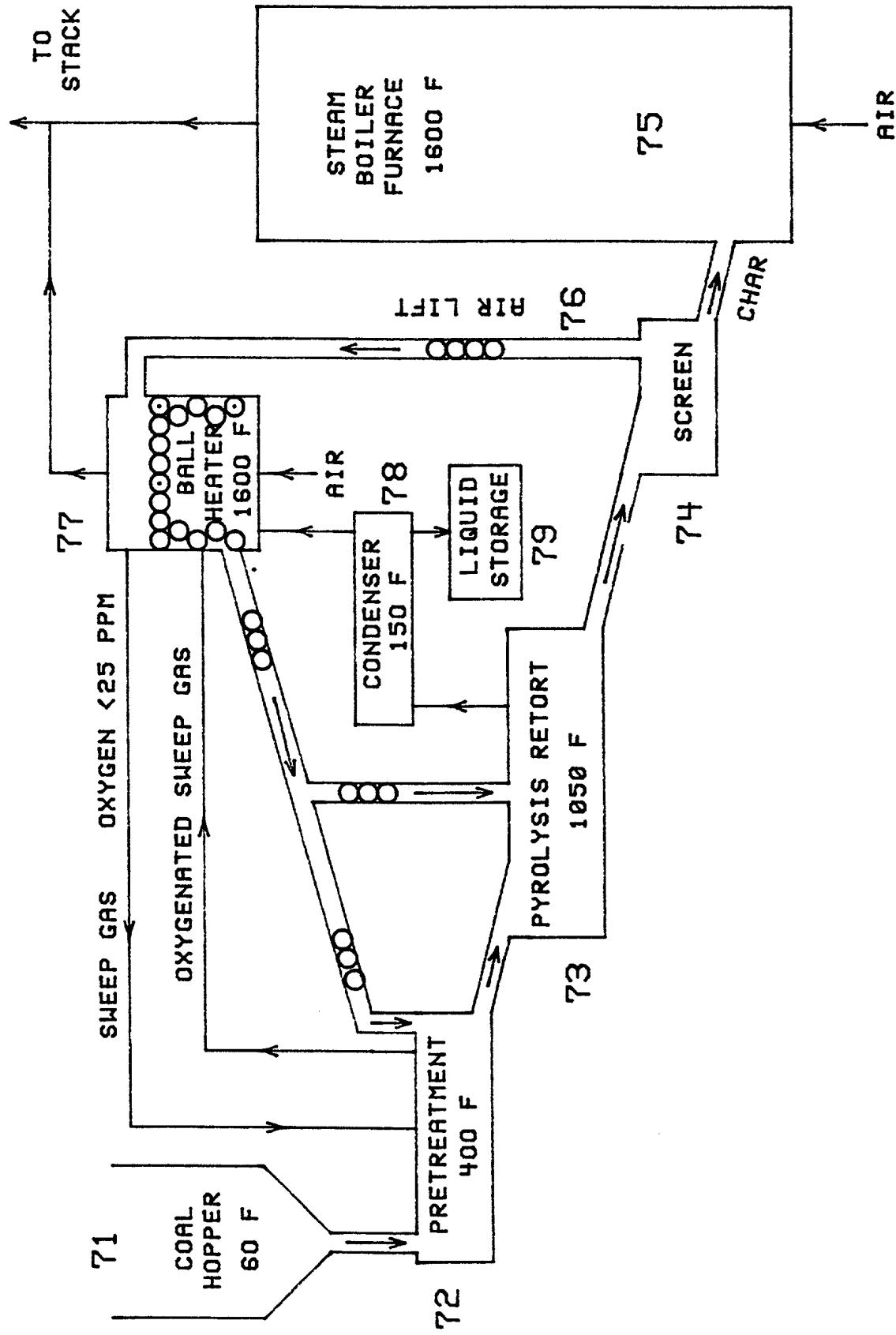
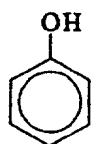
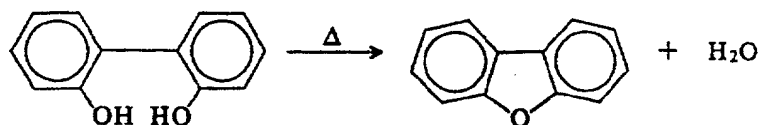
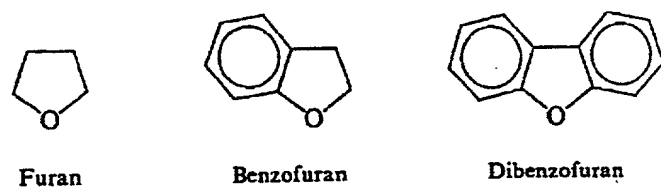
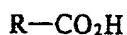


FIG. 2 COAL PRETREATMENT SYSTEM INCORPORATED IN A PYROLYSIS PROCESS UTILIZING CERAMIC BALLS FOR TRANSPORTING HEAT BETWEEN COMPONENTS

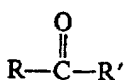
The most common form of heterocyclic oxygen is in furan ring systems:



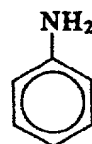
Phenol



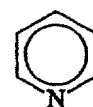
Carboxylic acid



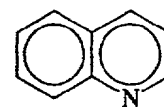
Carbonyl



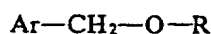
Aniline



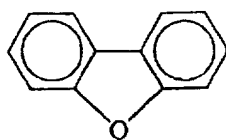
Pyridine



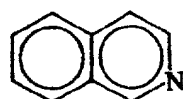
Quinoline



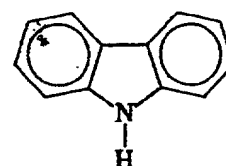
Ether



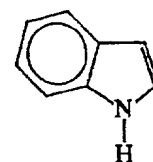
Heterocyclic oxygen



Isoquinoline



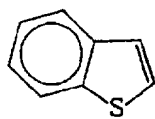
Carbazole



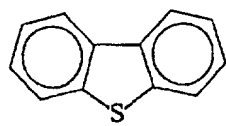
Indole



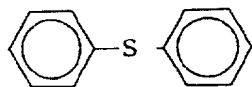
Thiophene



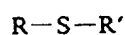
2,3-Benzothiophene



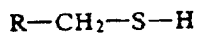
Dibenzothiophene



Diphenyl sulfide



Alkyl sulfide



Thiol

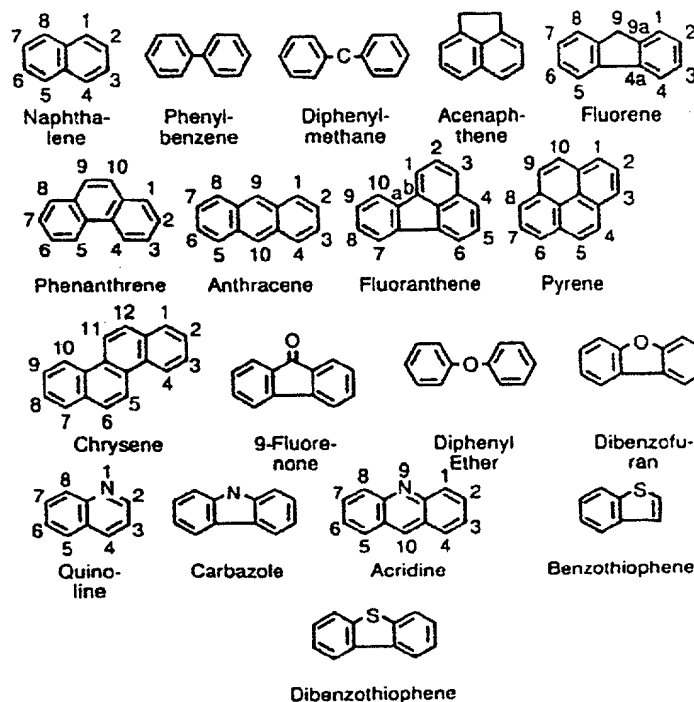


FIG. 3A Structure of selected model compounds.

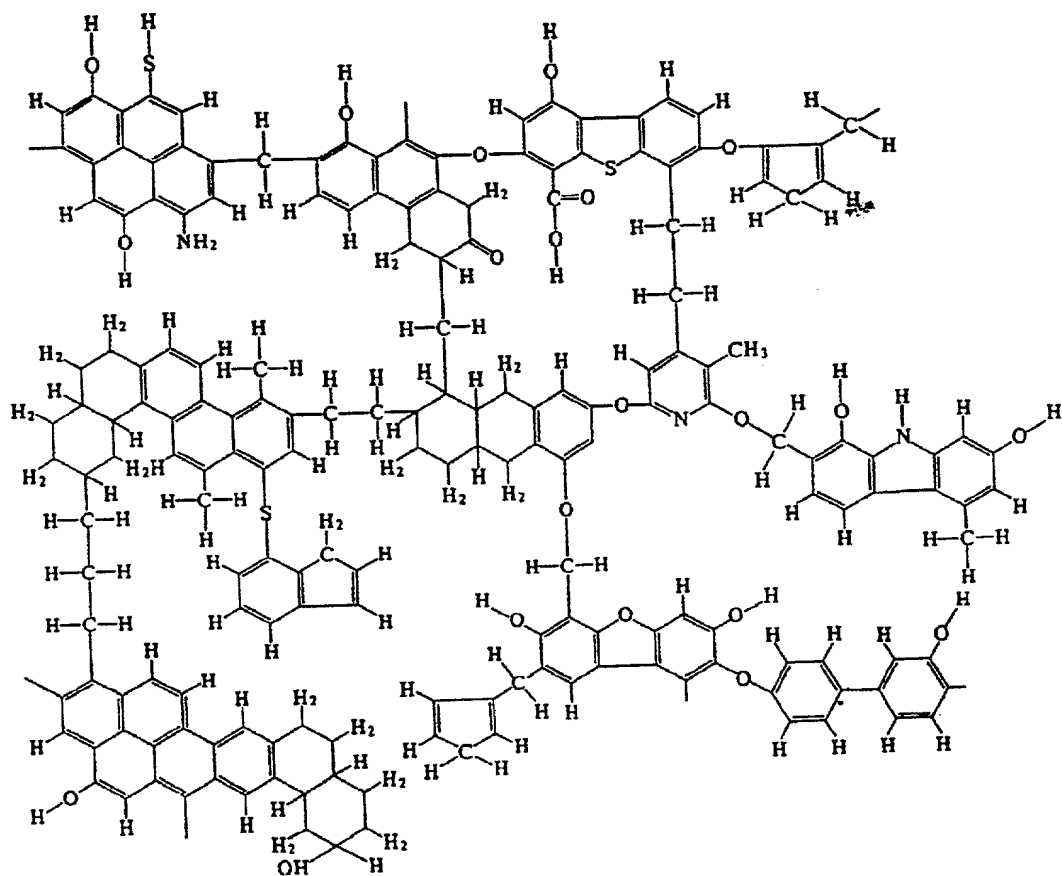


FIG. 3B Wisner model for bituminous coal. (Source: Reprinted with permission from W.H. Wisner, "Schematic Representation of Structural Groups and Connecting Bridges in Bituminous Coal," 1978.)

FIG. 4

GLASS SYSTEM PYROLYSIS TESTS

TEST NO. 10 - DEGASSING

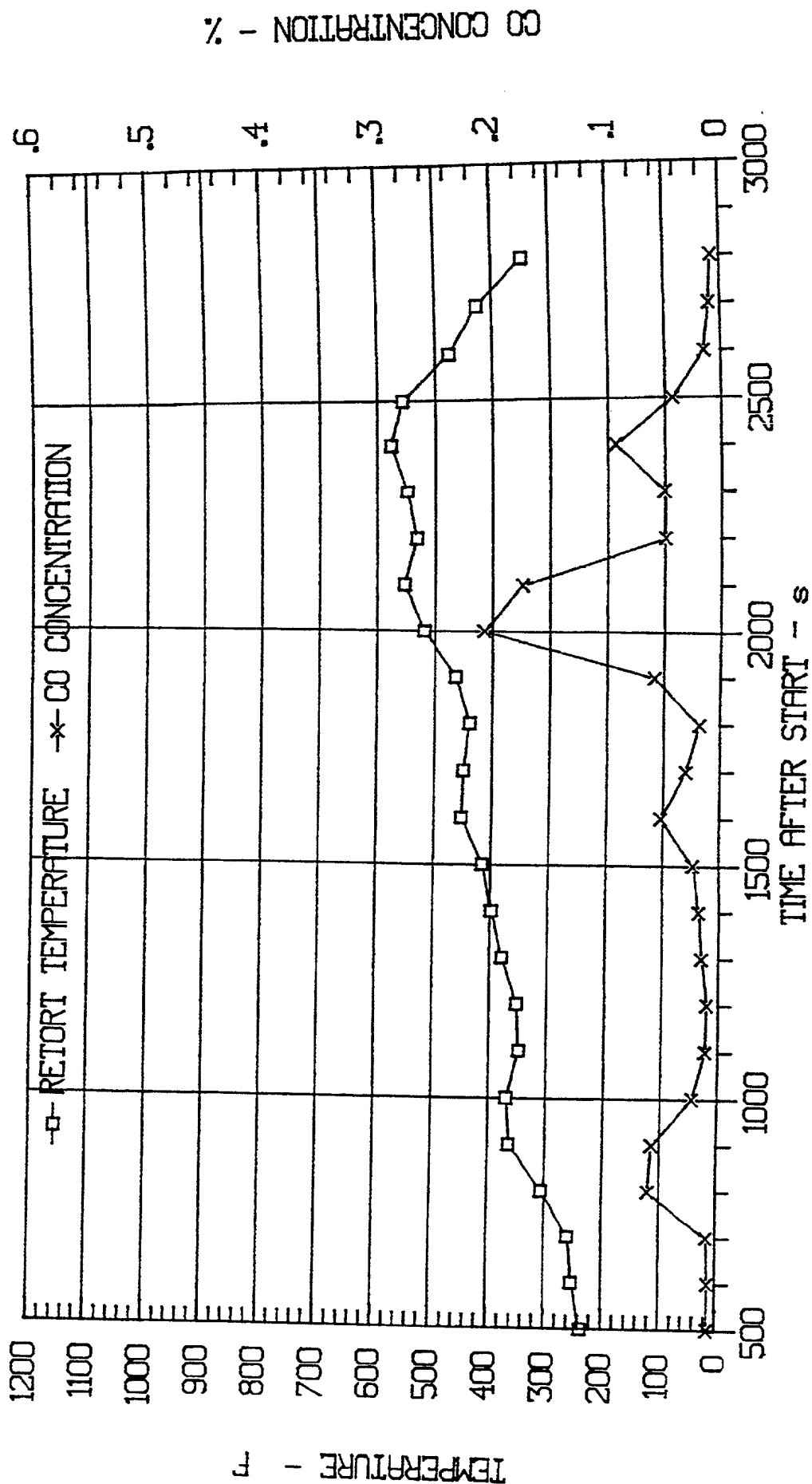
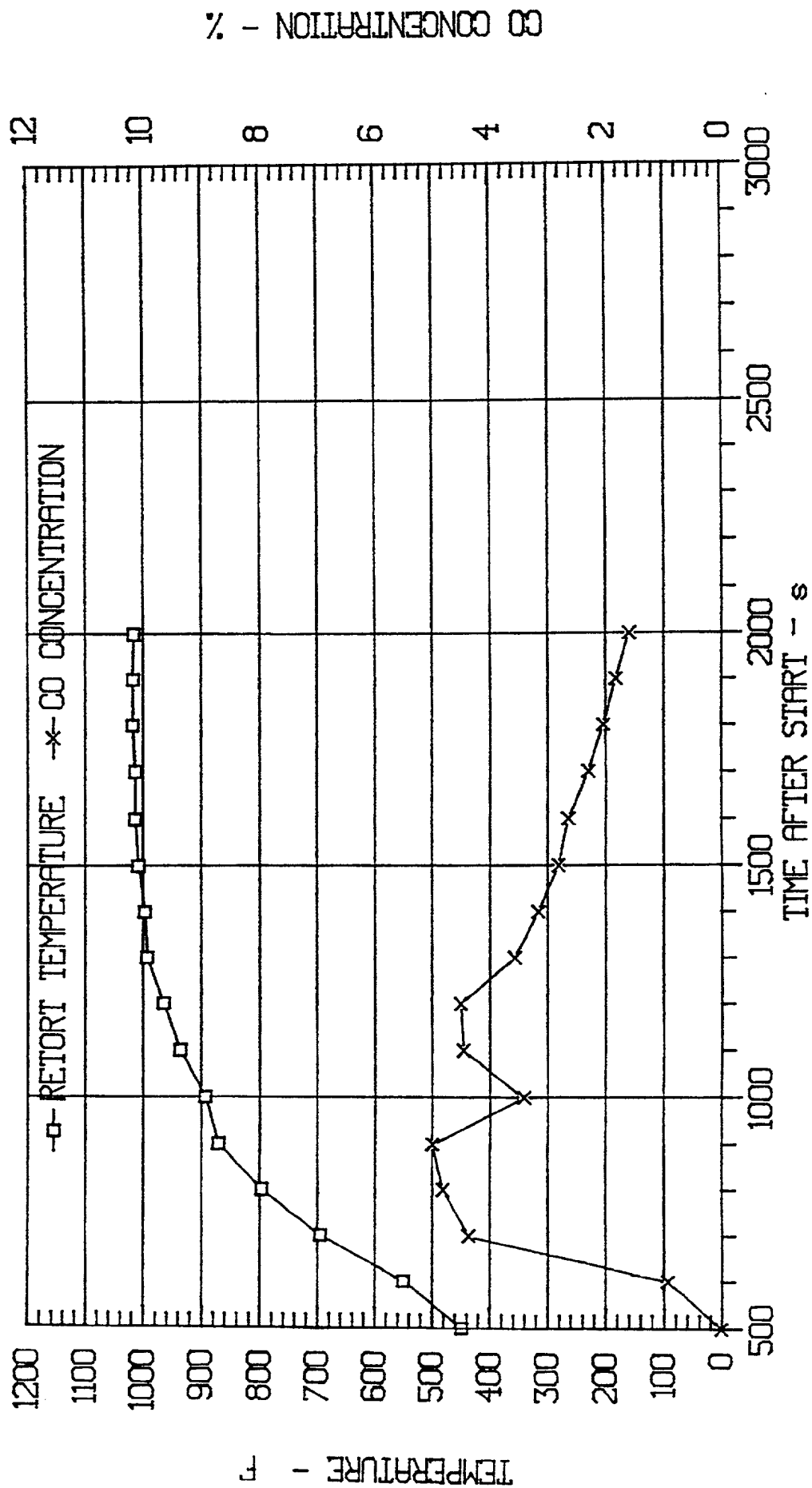


FIG. 5

GLASS SYSTEM PYROLYSIS TESTS

TEST NO. 10 - PYROLYSIS



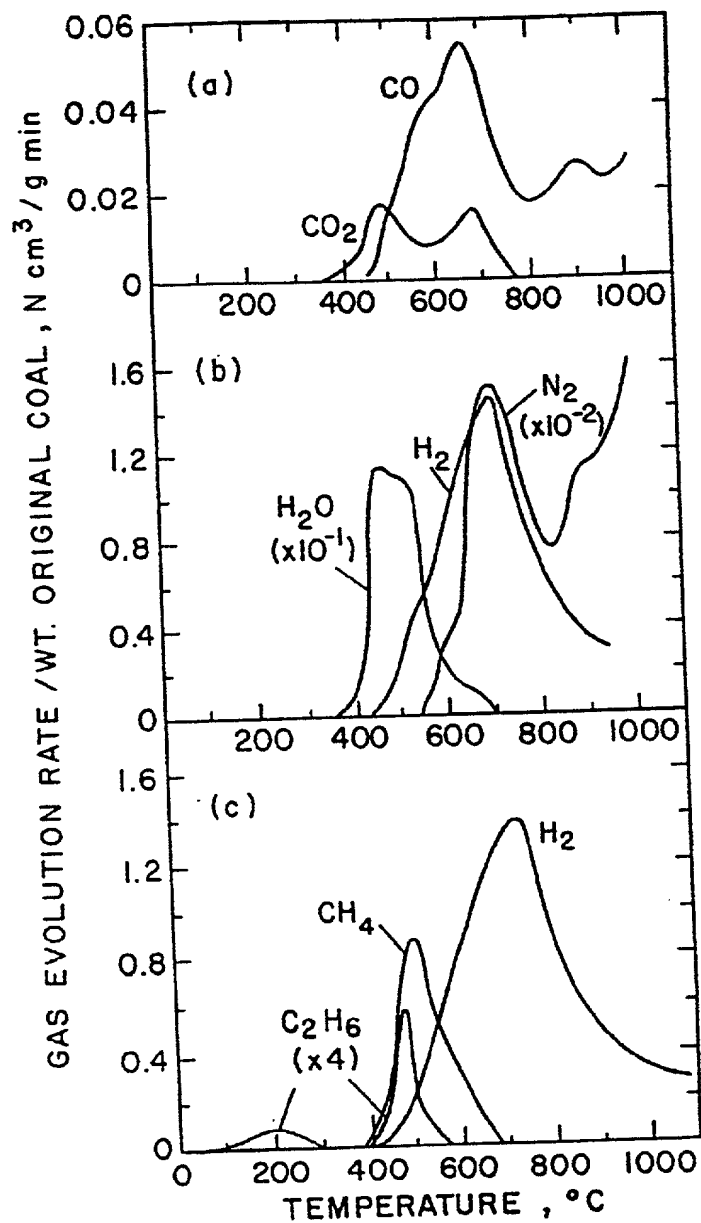


FIG. 6 Variation of Gaseous Species Evolution with Temperature during Coal Pyrolysis at Constant Heating Rate [(a) and (b), data of Klein (1971): Gustav coal, VM = 29 wt. % (MAF): heating rate = 1°C/min. (c), data of Jüntgen and Van Heek (1968): VM = 19.1 wt. %; heating rate = 2°C/min].

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FIG. 7 Oxygen concentration in the off-gas and pretreatment bed temperature as functions of time from initiation of nitrogen purge.

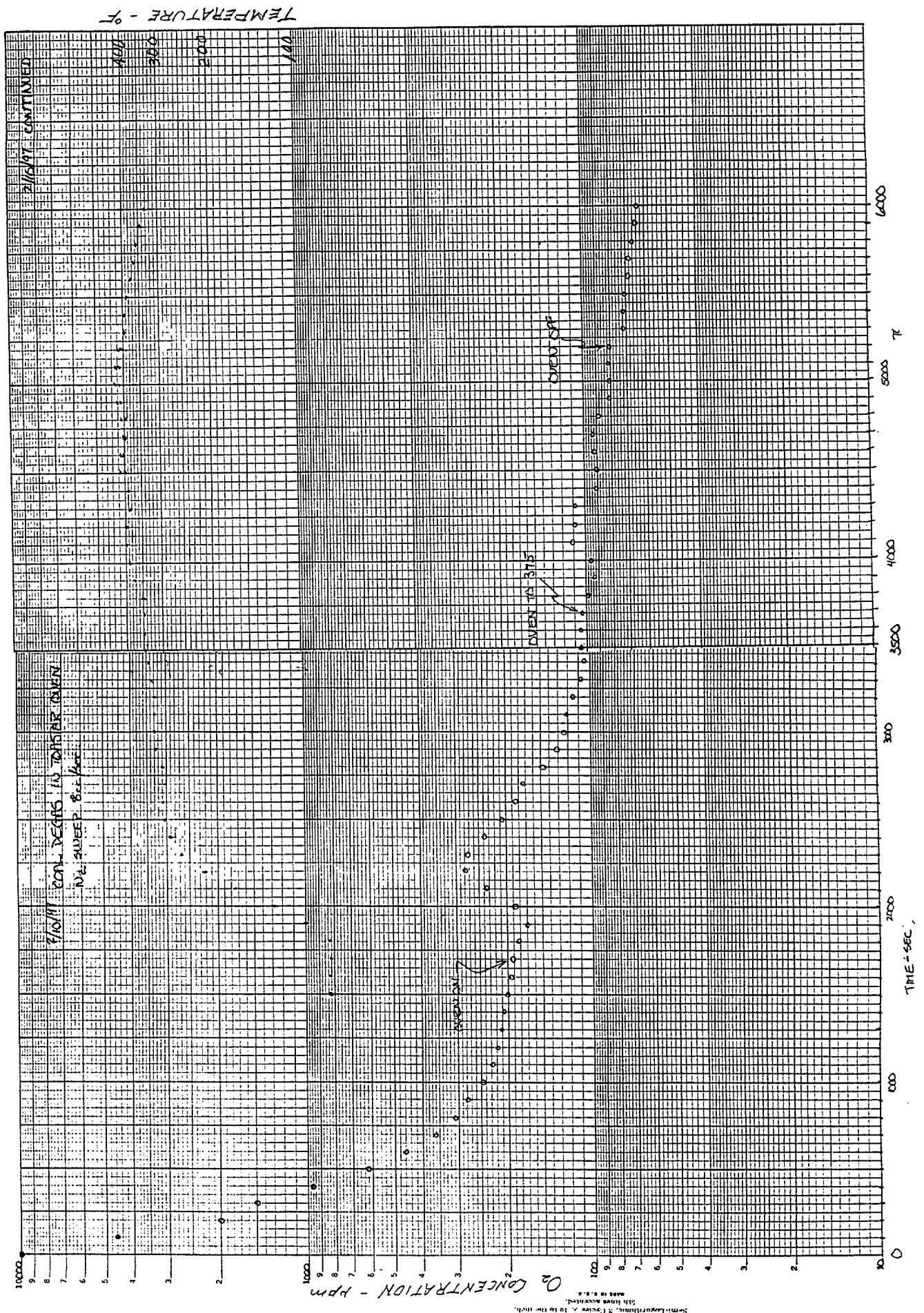
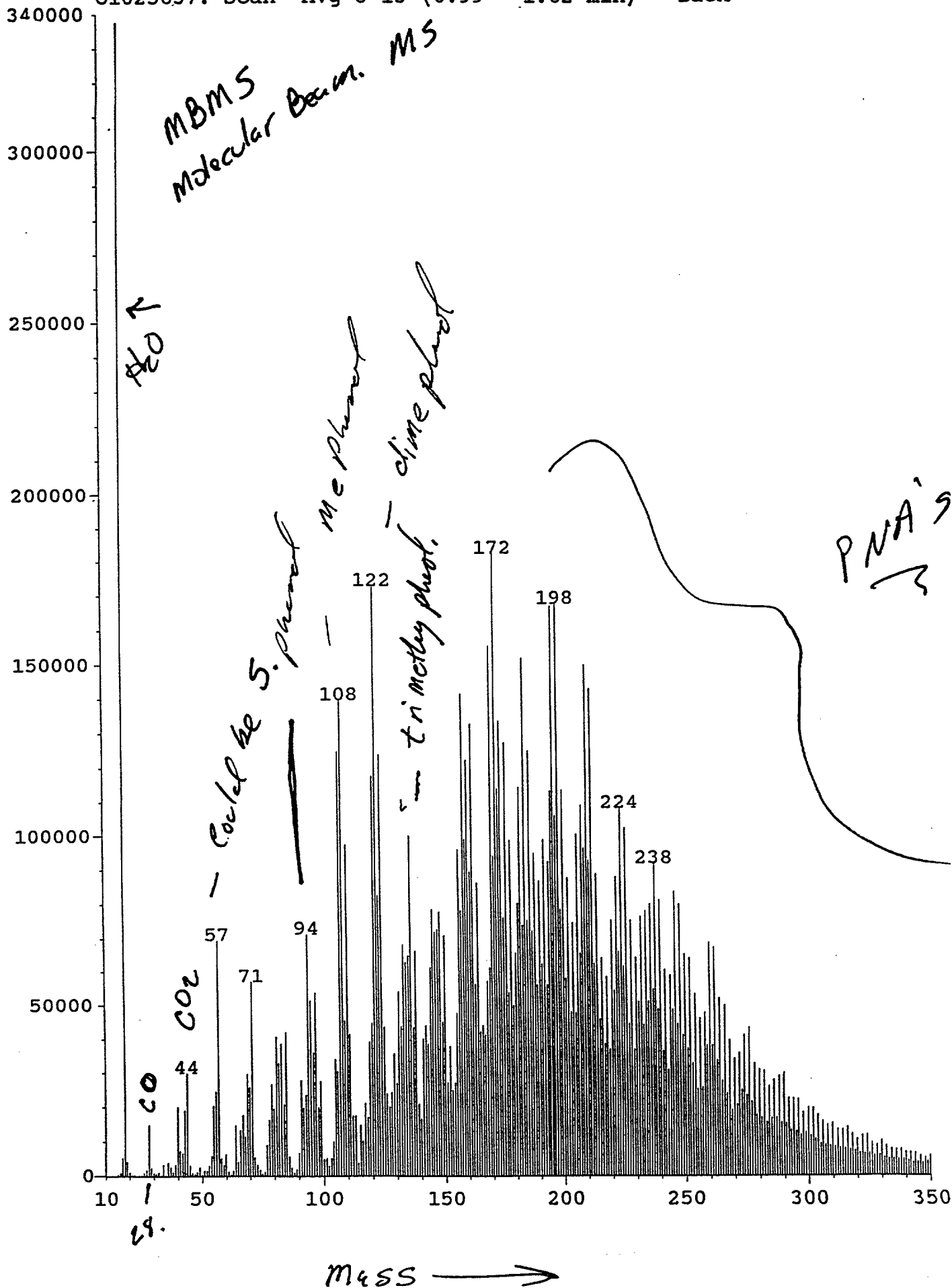


FIG. 8 Mass spectrograph for pyrolysis product liquid after pretreatment at 450°F to remove oxygen. (Courtesy NREL)

01025637: Scan Avg 8-13 (0.99 - 1.62 min) - Back



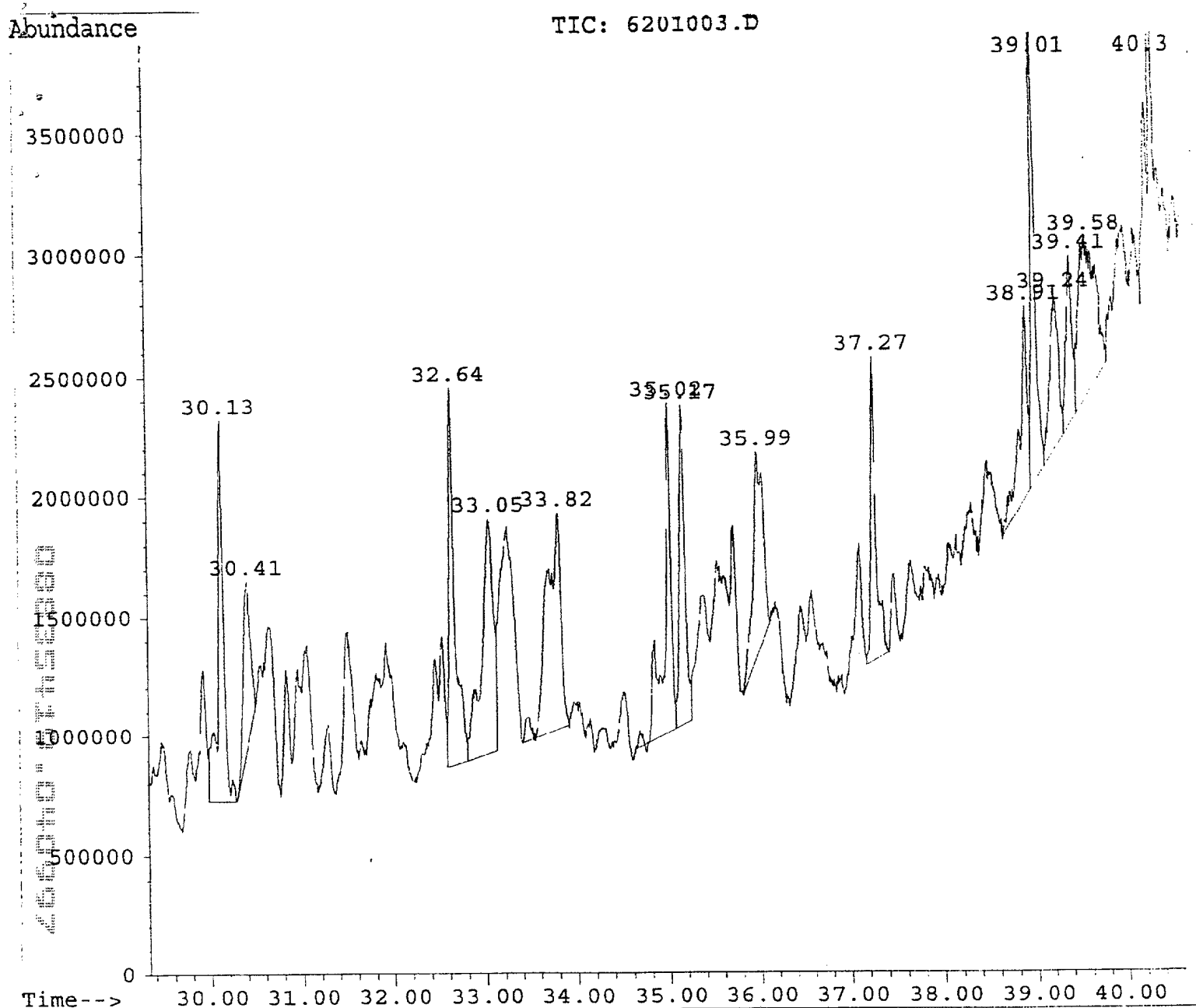


FIG. 9 Expanded version of the molecular weight region from 30 to 40 from the same data as for Fig. 8. The abscissa scale has been increased by a factor of 10 to facilitate interpretation of the fine structure.

K 39.10 mol wt.

S 32.08 " "

No 20.94 " "

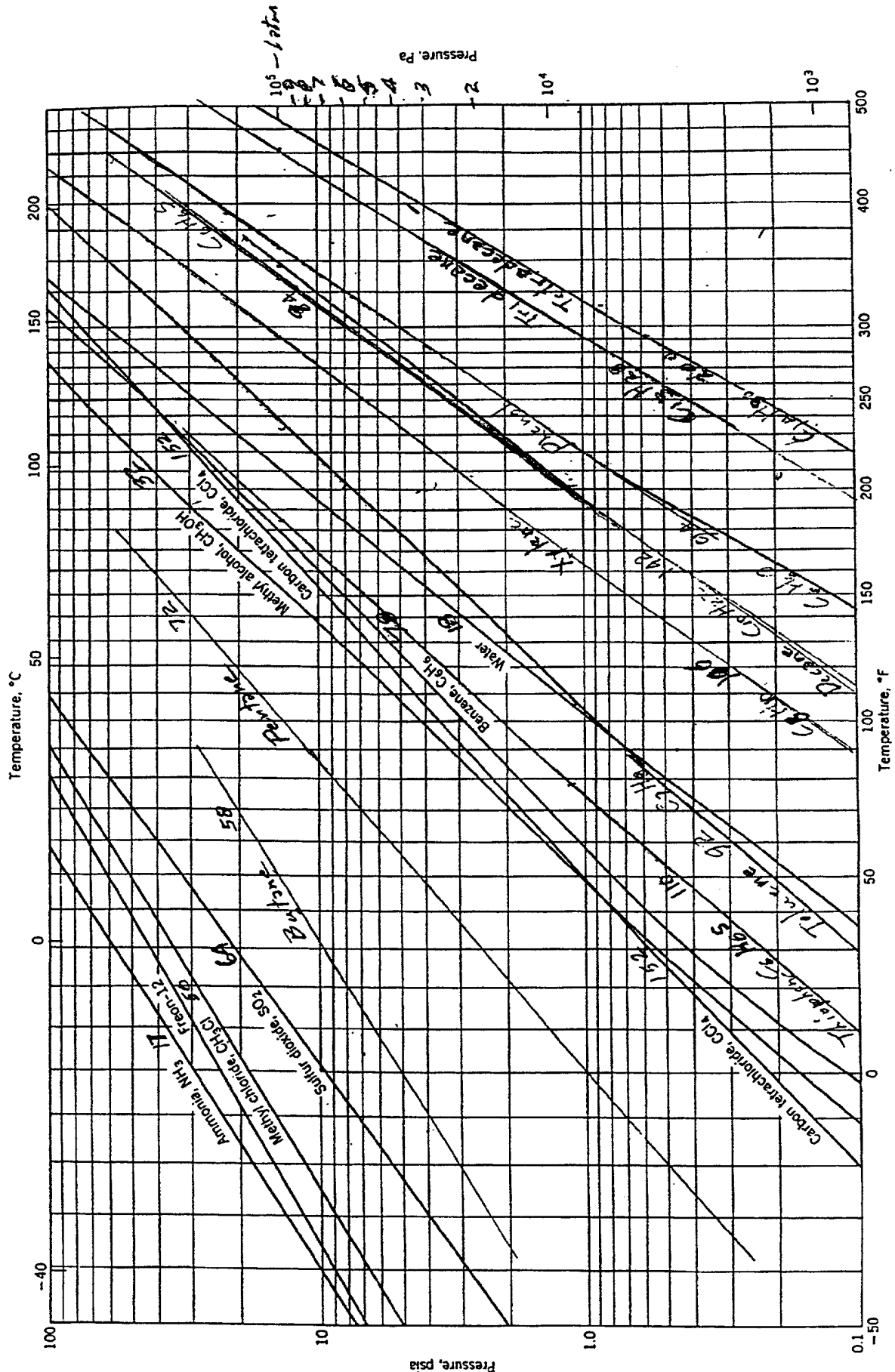


FIG. 10 Effects of temperature on the vapor pressure of typical liquids.

$$\text{Hydrocarbon concentration (by wt), ppm} = (\text{Vap. Press. atm}) \frac{(M_o) \text{ Wt.}}{28}$$

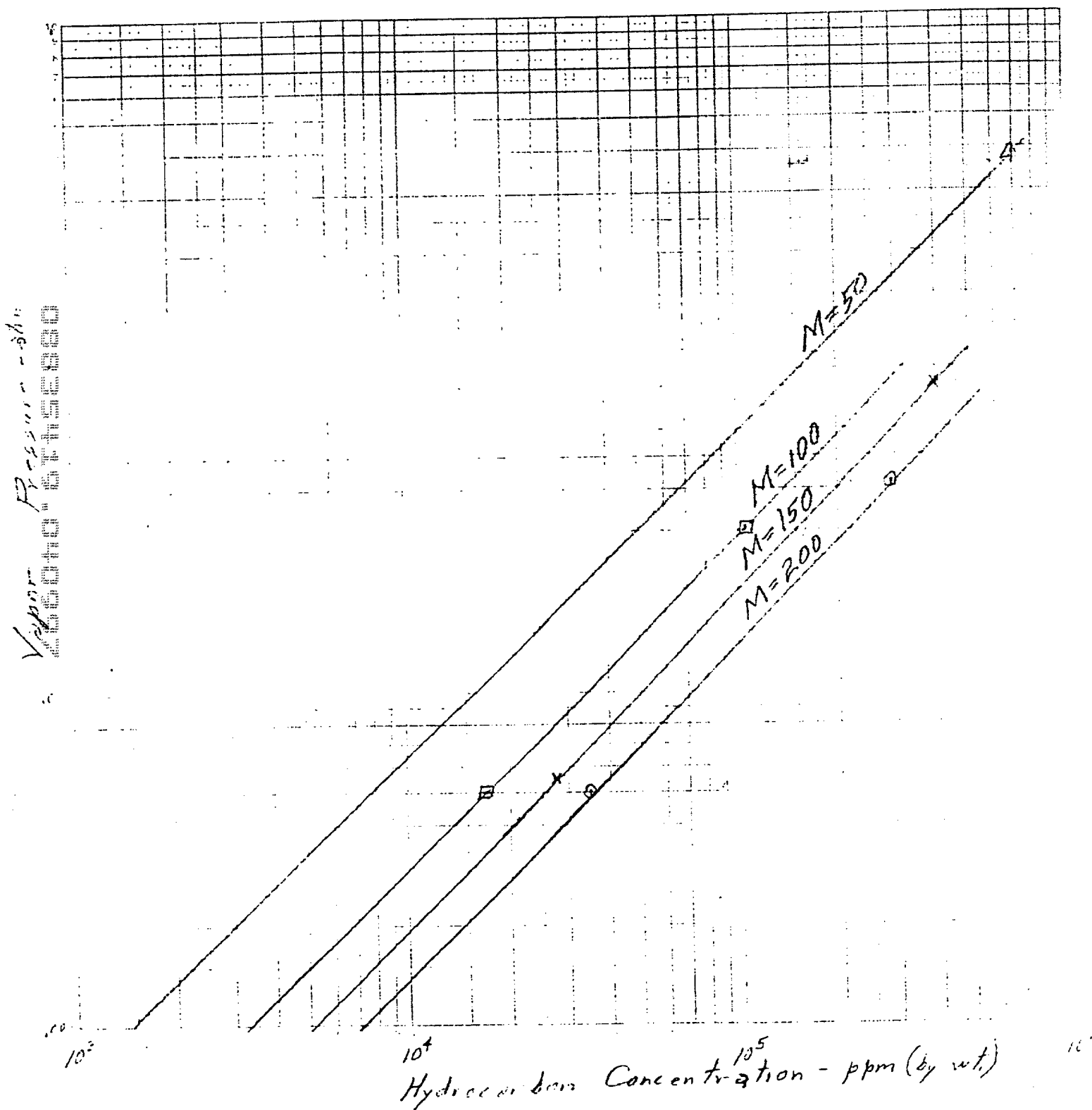


FIG. 11 Vapor pressure as a function of hydrocarbon concentration.

$$\text{Hydrocarbon Emission, g/min-g coal} = \frac{60}{10^6} (\text{N}_2/\text{s-g coal}) (\text{HC conc. in N}_2\text{-ppm})$$

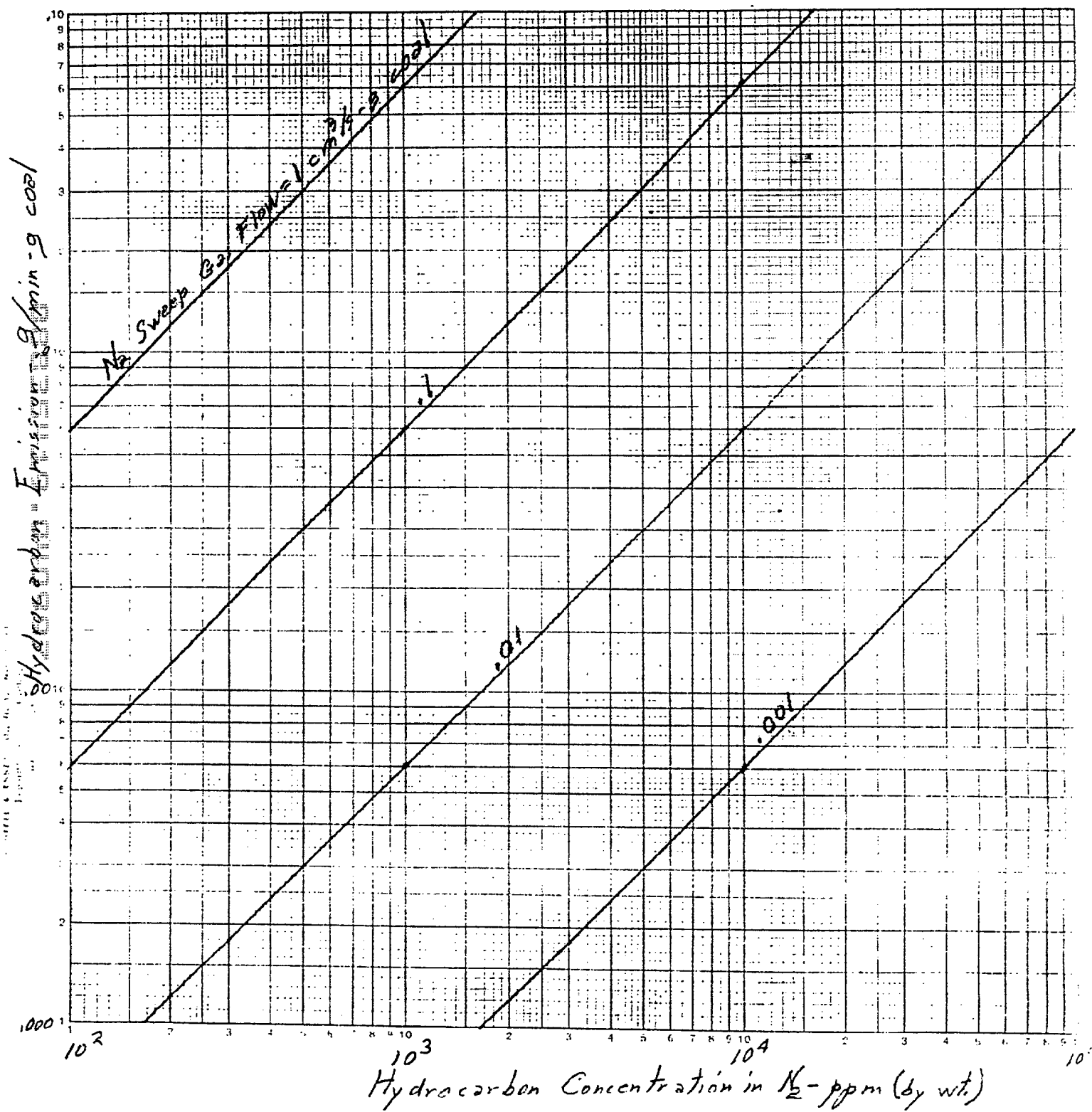


FIG. 12 Hydrocarbon emission as a function of concentration in N₂.